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Climate change, permafrost degradation, and infrastructure adaptation: preliminary results from a pilot community case study in the Mackenzie valley

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Abstract: Regional studies show that permafrost will disappear partly or completely over large areas of the north should predicted climate change occur. Much of the infrastructure in northern communities relies on the properties of frozen materials for stability. Ground warming could degrade the performance of existing structures. The Geological Survey of Canada is initiating an assessment of infrastructure needs in the north, by examining sensitivity to impacts of permafrost degradation under climate warming, using a community-level approach in the Mackenzie valley. Over the last century, this area has undergone the most warming in Canada and mean annual air temperatures are predicted increase up to 4° or 5°C in the next century. Preliminary results are presented of the pilot study at Norman Wells, Northwest Territories, where surficial geology, permafrost, and geotechnical conditions are described, and performance and sensitivity of infrastructure are examined.

Résumé : Des études régionales montrent que, par suite du réchauffement climatique, le pergélisol disparaîtra en partie ou en totalité sur de vastes étendues dans le nord canadien. La stabilité des infrastructures dans les collectivités nordiques dépend des propriétés du pergélisol, dont le réchauffement pourrait réduire la performances des structures existantes. Le présent projet utilise une approche à l'échelle des collectivités dans la vallée du Mackenzie pour évaluer les besoins des infrastructures nordiques et la sensibilité de ces infrastructures aux répercussions de la dégradation du pergélisol. La vallée du Mackenzie est la région du Canada dont le climat qui s'est réchauffé le plus au cours du siècle dernier et, selon les prévisions, la température annuelle moyenne de l'air devrait y augmenter de 4° à 5° C au cours du siècle prochain. Nous présentons les résultats préliminaires portant sur la cartographie, les conditions du pergélisol etles données géotechniques des matériaux, et sur la performance et la sensibilité des infrastructures à Norman Wells (Territoires du Nord-Ouest).

INTRODUCTION

Regional studies such as Environment Canada's Mackenzie Basin Impact Study (Cohen, 1997) and the Canada Country Study — Arctic Region (Maxwell, 1997), and Natural Resources Canada's Physical Environment of the Mackenzie valley (Dyke and Brooks, in press) show that permafrost will disappear partly or completely over large areas of the north should predicted climate change occur. The design of much of the infrastructure in northern communities relies on the properties of frozen materials for stability. Warming of the ground could degrade the performance of existing structures (Etkin, 1998). Problems have occurred with roads, foundations, utilities, and embankments due to permafrost thaw associated with both natural and anthropogenic changes. Future climate warming could increase or cause problems affecting the integrity of both existing and new infrastructure. Under the Government of Canada's Climate Change Action Fund and the Geological Survey of Canada's Hazards and Environmental Geoscience Program, a project has been initiated to assess infrastructure needs in northern communities under a scenario of climate warming. It will use a case-study approach in several communities in the Mackenzie valley to examine the sensitivity of infrastructure to permafrost degradation. The communities studied will span a range of permafrost and terrain conditions, from continuous through discontinuous permafrost and cold through warm ground temperatures.

This paper presents preliminary results from the first phase of work at the pilot study community of Norman Wells, Northwest Territories, and focuses on surficial geology, permafrost conditions, geotechnical properties of frozen materials, and infrastructure compiled into a database for the determination of permafrost distribution, temperatures, and performance history. Geotechnical data from over 400 boreholes near Norman Wells have been thicknesses, the distribution of unconsolidated deposits and bedrock depth, water content variation by genetic origin, and deposit texture. Physical, mechanical, and geotechnical properties of frozen ground at Norman Wells were also analyzed. Types of infrastructure and foundation systems were identified and classified, and the performance of past and existing infrastructures in Norman Wells was examined and summarized.

CLIMATE CHANGE AND PERMAFROST CONDITIONS IN THE MACKENZIE VALLEY

Permafrost covers approximately 50% of Canada and is widespread in the Mackenzie valley (Fig. 1, inset). In the southern part of the Mackenzie valley, permafrost is sporadic and not more than a few meters thick. Towards the north, it becomes gradually more abundant and thicker. Ice-rich, thaw-sensitive, Quaternary deposits cover large parts of the Mackenzie valley, which is therefore very sensitive to ground warming due to climate change (Aylsworth et al., in press).

Climatic records have been kept for over 40 years at several stations in the Mackenzie valley. Air temperatures in the Mackenzie valley have warmed by some 1.7°C over the past century (Environment Canada, 1995). Temperatures at Norman Wells have increased by 1.15°C over the last 50 years. In addition, 1998 was the warmest year on record in Canada. According to climate warming scenarios based on global circulation models, global annual mean temperatures will increase by 1–3.5°C relative to the present by 2100 (Maxwell, 1997). Warming is expected to be amplified in northern regions and the projected changes are expected to be greatest in winter and spring (Maxwell, 1997).

In many parts of the central and southern Mackenzie valley, permafrost temperatures are warm, generally between 0°C and ~2°C. Thus, even small changes in ground temperatures associated with increased air temperatures will likely reduce the extent of permafrost, increase the depth of the seasonally thawed layer (active layer), and cause ground ice to melt. Potential direct infrastructure-related consequences of such permafrost degradation are a loss of bearing capacity by certain soils and foundation systems, a decrease in soil creep resistance, an increase in thaw depth and settlement, and changes in ground permeability. On the basis of these climate-change scenarios, such geotechnical problems are anticipated to be more and more common, leading to serious and certainly costly problems or maintenance requirements for northern communities and infrastructure.

THE PILOT STUDY: NORMAN WELLS

The pilot study community of Norman Wells (lat. 65°17′N, long. 126°50′W, elevation 73 m a.s.l. at the airport) is on the east bank of the Mackenzie River, 145 km south of the Arctic Circle (Fig. 1). Unlike other settlements in the Mackenzie River valley that originated as fur trading posts, Norman Wells was the first community in the Northwest Territories to be established entirely as a result of the development of non-renewable resources. An oil refinery has operated in the community since 1932 and a major capacity upgrade coincided with the construction, in the early 1980s, of an 869 km pipeline from Norman Wells to Zama, Alberta. Norman Wells also serves as a regional centre for the Sahtu area and gained town status in 1992. The population is closely linked to the economic health of the oil industry. The early population varied from about 300 in 1961 to a peak of 749 in 1985. Norman Wells is of interest for this project as it contains a much larger proportion of large-scale infrastructure than its population would suggest, primarily because of its reliance on the oil industry. Preliminary geothermal modelling predictions indicate that thaw depths will increase dramatically and permafrost may disappear at many sites in the Norman Wells area (Burgess et al., in press). The Geological Survey of Canada also has a long history of research in the area.

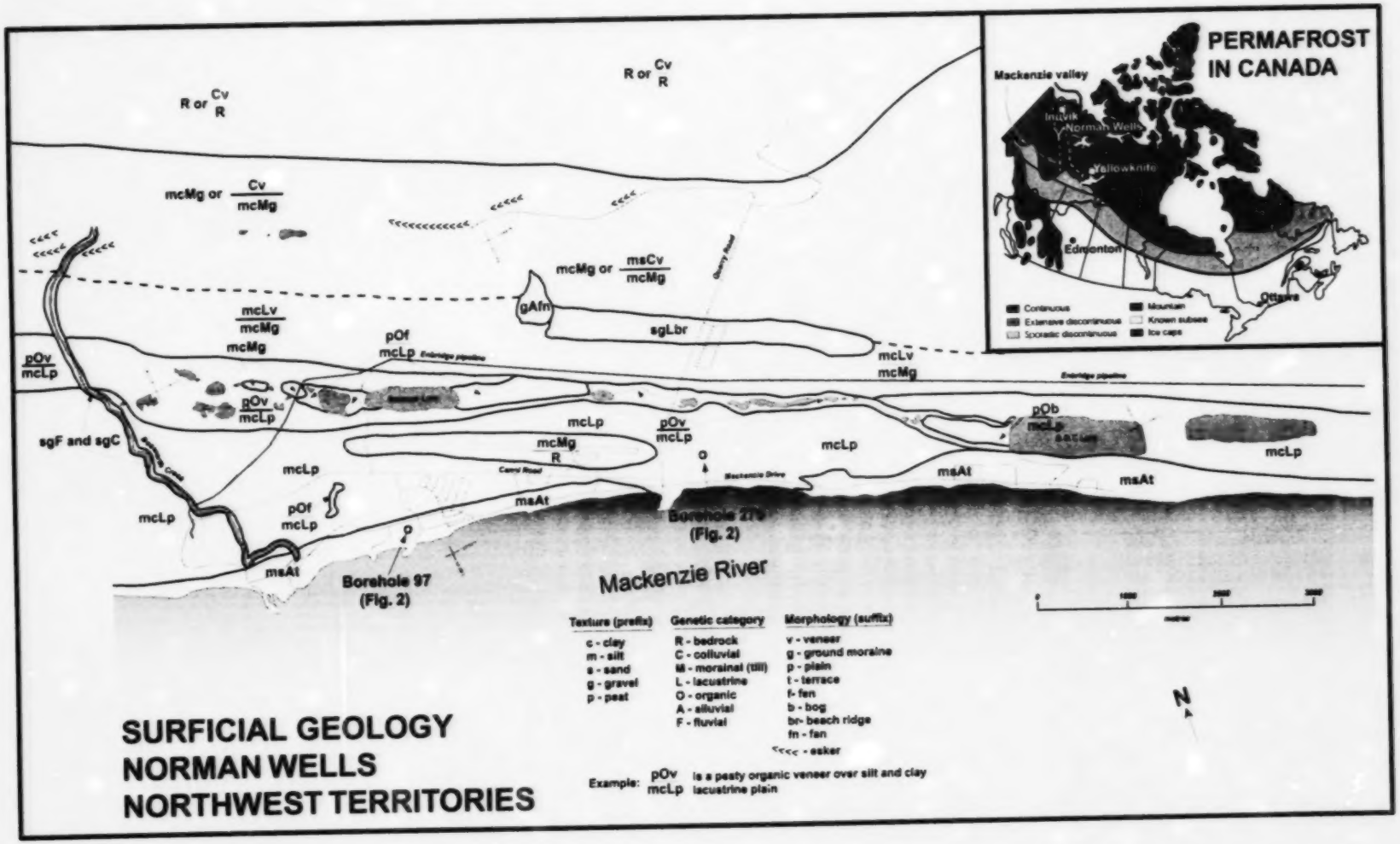

Figure 1. *Surficial geology of Norman Wells and permafrost distribution in Canada (inset; after Heginbottom et al., 1995).*

Surficial geology and permafrost conditions

Large-scale surficial-geology mapping was undertaken initially in this area by Hanley (1973). Subsequent more detailed mapping has been conducted in the Norman Wells area mainly for development and infrastructure purposes (e.g. Hardy Associates, unpub. rept., 1981; Thurber Consultants Ltd., unpub. rept., 1986; Canuck Engineering Ltd., unpub. rept., 1984). An updated map of the surficial geology of the Norman Wells area (Fig. 1) was compiled from a re-examination of previous work, 431 borehole logs collected from consultants' reports, the Mackenzie Valley Geotechnical Database (updated from Lawrence and Proudfoot, 1976), and recent aerial photographs.

Unconsolidated, postglacial deposits are confined to a zone between the Mackenzie River and the Norman Range about 3 km north of Norman Wells. Boundaries of surficial geology units are generally parallel to the banks of the Mackenzie River. The northernmost sector within the limits of the Norman Wells map area, including the shale and limestone quarries, is essentially covered by a thin veneer of colluvium on rock or by exposed bedrock. Immediately south, the area is characterized by silty and clayey till (ground moraine), locally with a thin veneer of colluvium. Several gravelly eskers occur in the ground moraine area. Silty and clayey glaciolacustrine deposits form a veneer over the till below an elevation of about 140 m and become thicker with flatter surfaces towards the river (lacustrine plain). A long, narrow depression in the glaciolacustrine deposits, parallel to and about 1 km from the river, is characterized by an organic veneer in places with thicker peat. A narrow band of silty and sandy alluvial materials forming terraces along the Mackenzie River underlies about 50 per cent of the developed (or inhabited) zone of Norman Wells, including much of area towards the river from D.O.T. Lake. Till immediately overlying bedrock is noted in some boreholes drilled through the lacustrine-plain and alluvial-terrace deposits. The airport has been constructed on a bedrock high covered with thin till just north of Canol Road.

Shale bedrock is found at 5 to 10 m depth throughout much of the developed town area. Shallower depths to bedrock occur in the north end of the residential area towards Canol Road and may be associated with the bedrock high underlying the airstrip. Depth to bedrock is greater than 20 m in areas near upper Bosworth Creek.

Permafrost distribution in this area is discontinuous, but widespread. The presence of groundwater springs leads to unfrozen conditions, notably near the alluvial fan about 1.5 km north of the airport runway and in several boreholes drilled east of Quarry Road and south of the pipeline. Pockets of unfrozen ground are also found near the banks of the Mackenzie River, in sandy alluvial material near D.O.T. Lake, in a swath paralleling the river across the north end of the residential area, and beneath lakes and rivers.

Permafrost thickness also varies greatly, ranging from no permafrost to 60 m of permafrost measured in one of ESSO's oil wells. Mean annual permafrost temperatures are generally no colder than ~3°C and are most commonly between 0°C and ~2°C (Fig. 2). Excess ice occurs commonly in the near surface of organic and fine-textured mineral soils. Permafrost is absent on Kee Scarp, a 344 m high ridge north of the town. Data from Taylor et al. (1998) suggest that thin or absent permafrost at elevations from 100 to 500 m a.s.l. is due to temperature inversions.

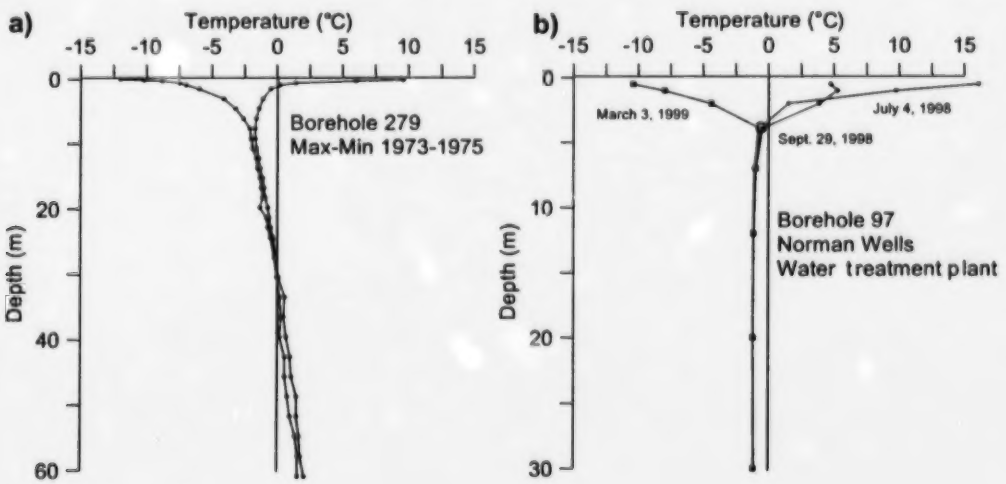

Figure 2. *Borehole temperature envelopes measured in* ***a)*** *borehole 279 drilled in undisturbed, forested terrain and 30 m of permafrost and* ***b)*** *borehole 97 drilled in an area cleared and covered with fill, beside a large water-treatment plant. Note that borehole 279 shows a gradient typical of increasing ground temperature with depth, whereas borehole 97 is essentially isothermal, suggesting a warming effect of disturbance associated with development.*

Properties of frozen ground in Norman Wells

Only a few research papers published in the last 30 years have presented geotechnical properties for the Norman Wells area (e.g. Lawrence, 1975; Lau and Lawrence, 1977). However, analysis of data from over 2000 samples in the updated Norman Wells database has provided detailed information on physical and geotechnical properties of soils in Norman Wells, such as grain-size distribution, water content, and plastic and liquid limits. Thermal properties have also been compiled for dominant material types in Norman Wells. A knowledge of all these properties is essential for the description of geomaterials and they will be integrated into subsequent soil-behavior analyses and mechanical and thermal modelling.

Grain-size distribution

Minimum and maximum grain-size curves are presented to illustrate the grain-size range for each of morainal, lacustrine, alluvial, and colluvial deposits (Fig. 3). With the exception of colluvial deposits, the distribution range for the materials is relatively large since the genetic classes of surficial deposits include a broad particle size range related to mechanisms of deposition. For instance, deposits of lacustrine origin contain materials from deep water-deposited clay to beach-deposited sand. Mean grain sizes follow the trend of colluvial (mean size particle at 50 per cent passing, or D_{50} = 70 mm) > morainal (3 mm) > lacustrine (1mm) > alluvial deposits (0.3mm).

Water content (w%) versus landform and materials

Mean gravimetric water content versus depth data have been compiled based upon both genetic class in which the borehole occurs and texture (clast size) of the individual sample (Fig. 4). As expected, organic material shows the highest mean water content, almost 200% near the surface decreasing to just over 100% at 3 m depth. Mean water content for other material is lower than 60%, with silt and clay showing higher mean gravimetric water contents than other materials. Mean water content data for clay and silt show a gradual yet significant decrease with depth from the surface to about 7 m. Water contents for sand, fill, gravel, and bedrock are slightly higher in the near-surface than at depth, yet mean gravimetric water content values generally remain below 20%.

Graphs of mean gravimetric water content versus depth based on landform types are not shown here, but preliminary results indicate that organic, lacustrine, and till (morainal) show a clear gradual decrease in water content from the ground surface to a depth of 7 m. At about 7 m depth, water content does not exceed 20% and tends to become independent of surficial landforms and depth. Near-surface water contents are greatest in lacustrine and thick organic over lacustrine terrain units.

Atterberg limits and other geotechnical properties

The characterization of soils in Norman Wells is planned to include the determination of several other physical and mechanical properties, such as Atterberg limits, density, void ratio, coefficient of consolidation, thaw strain, strength to cone and SPT penetration, and many others where available. Mean gravimetric water content (w%), plastic limit (w_P), and

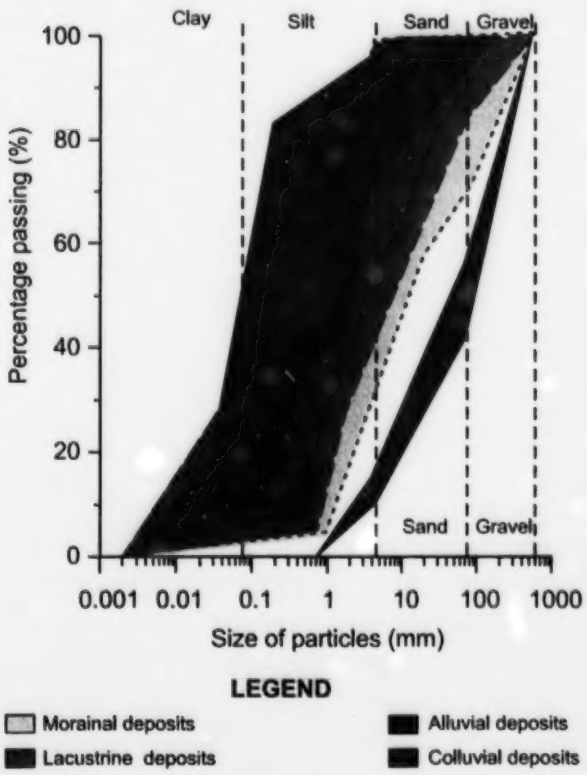

Figure 3. Grain-size distribution envelopes for genetic classes of surficial deposits at Norman Wells.

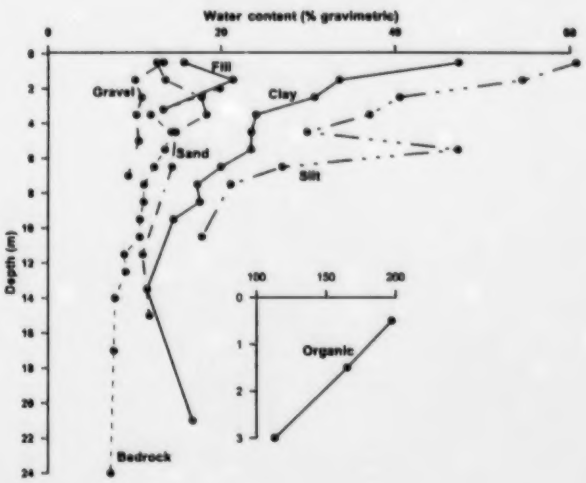

Figure 4. Mean gravimetric moisture content for various materials by texture at Norman Wells.

liquid limit (w_L) are presented in Table 1. Values of mean gravimetric water content correspond to the average of the samples taken from the ground surface to 4 m depth presented in Figure 4. Except for the organic material, which shows a high plasticity, all the materials show moderate to low plasticity, which indicates a fair to low range of water content in which the material exhibits plastic behavior.

Thermal properties

A knowledge of thermal properties of soil is of great importance to engineering projects in permafrost, as these influence the thawing or freezing rate (Nixon and McRoberts, 1973). A knowledge of thermal property values is necessary for a description of frozen ground used in thermal modelling of the interaction between climate, frozen ground, and infrastructure. The freezing-characteristic curve (unfrozen water content as a function of temperature below 0°C) is also important owing to its effect upon mechanical and thermal properties of the ground. Table 2 summarizes the mean values for two of the most important thermal properties, thermal conductivity (k) and heat capacity (c) measured or calculated for frozen and unfrozen ground in Norman Wells.

Table 1. Mean values of Atterberg limits and indexes for soils at Norman Wells.

Soils	w%[2]	w_p	w_L
Clay	34	19.9	34.2
Silt	48	30.4	41.9
Organic[1]	158	43	68
Gravel or Fill[1]	11	10.6	25.4
Sand	16	20.2	20.7

[1]Only one sample available
[2]Mean value for the first 4 m depth from the surface (*see* Fig. 4)

Infrastructure and foundation systems in Norman Wells

Construction and foundation types

The thermal impact from construction and long-term facility operations, as well as conventional requirements and seasonal frost (or thaw) effects, must be taken into account in permafrost regions. Frozen soils usually have a very strong bearing capacity and, as such, design capacity is typically based on preserving frozen conditions or limiting thaw to constrain infrastructure movements to within tolerable levels. In permafrost regions, the choice of a foundation system is a function of frozen-ground thermal stability and infrastructure loads. The latter can be considered constant over a long period; however, with the observed recent trend of climate warming and the potential for future warming, the long-term thermal stability of permafrost cannot be assumed, especially in areas with thaw-sensitive permafrost. Permafrost thaw can lead to significant negative consequences for infrastructure integrity in terms of loading capacity and differential movement. The relationship between climate change, permafrost degradation, and infrastructure thus becomes a major concern for northern communities.

Various infrastructure and construction types are found in the town of Norman Wells. A survey of the existing infrastructure and associated foundations was undertaken. Infrastructure surveys had two main objectives, 1) to classify the construction types and the foundation systems and 2) to evaluate infrastructure performance history and problems. A classification of 14 construction types was established mainly on the basis of types of economic activity. In all, over 400 individual items of infrastructure exist in Norman Wells, including single- to multiple-unit houses (Fig. 5a), local and

Table 2. Thermal properties for permafrost at Norman Wells.

Materials	Conductivity Frozen (W/m.K)	Conductivity Unfrozen (W/m.K)	Frozen heat capacity or volumetric heat capacity (c or C) (kJ/kg.K or MJ/m³.K)	Unfrozen heat capacity or volumetric heat capacity (c or C) (kJ/kg.K or MJ/m³.K)
Peat (1)	2.00	0.553	2.05 kJ/kg.K	2.97 kJ/kg.K
(3)	0.37–1.8		1.23–4.12 MJ/m³.K	
Dry crushed limestone (2)	1.729	2.074	0.75 kJ/kg.K	0.84 kJ/kg.K
Dry crushed shale (2)	1.729	2.074	0.71 kJ/kg.K	0.79 kJ/kg.K
Silty-clay (2)	1.867–2.04	0.968–1.366	1.08–1.21 kJ/kg.K	1.55–1.88 kJ/kg.K
(1)	1.867–2.178	0.985–1.729	1.30–1.21 kJ/kg.K	1.30–1.88 kJ/kg.K
(3)	0.81–2.37		1.81–3.47 MJ/m³.K	
Sand (3)	2.19–3.90		2.032.86 MJ/m³.K	
Shale (2)	2.161–2.403	1.625–2.074	0.88–1.0 kJ/kg.K	1.05–1.34 kJ/kg.K
(1)	1.158	1.124	0.836 kJ/kg.K	1.045 kJ/kg.K
(3)	1.22–1.46		2.08–2.29 MJ/m³.K	

(1) *after* Dillon Consulting Engineers and Planners, unpub. rept., 1976
(2) *after* EBA Engineering Consultants Ltd., unpub. rept., 1977
(3) *after* Burgess, 1983

regional government buildings (Fig. 5b), roads, oil and water storage tanks (Fig. 5c), airstrip and terminal building, dam and berms, utilidors, or docking facilities. Technical reports exist for 54 specific items of infrastructure in Norman Wells, such as housing, recreational buildings, facility service installations, and their associated foundations.

A foundation classification system was established on the basis of three components: foundation types, materials used, and specific technical details. Foundation systems used in Norman Wells are varied and include shallow foundations (i.e. sills, post and pad system, footings, piers, mat or raft, pad and fill (Fig. 5c), and slab), and deep foundations (i.e. timber, steel (Fig. 5b), and reinforced concrete piles). Special foundations or geotechnical solutions, such as thermosyphons (thermal piles where the mechanical circulation of gas or liquid inside the pile maintains frozen conditions in the ground) and ventilated gravel pads (Fig. 5c) are used in some cases.

Figure 5. a) New house with screw jacks as a foundation system (screw jacks allow the building to react to minor vertical ground displacement); b) territorial government office building on steel H-beam piles; and c) oil storage tanks standing on a gravel berm with 30 cm diameter ventilated ducts.

Foundation systems used in Norman Wells have made significant progress over the last 50 years owing to advances in geotechnical engineering in permafrost areas, as well as a reliance on the large-scale infrastructure of the oil industry. The first pile foundation in Norman Wells used native spruce because of the high shipping costs of imported timber. Owing to the availability of scrap pipes (development of oil industry), steel pipe piles have been used extensively since 1947. They are available free of charge, easily handled and driven, and quickly lengthened, cut, or capped by welding.

Currently, approximately 49 per cent of housing units are built on timber sills, 29 per cent on steel pipe piles and steel H-beam piles (Fig. 5b), and almost 11 per cent on screw jacks (Fig. 5a). The remainder involve several types of foundation systems such as steel and timber posts or timber transverse sills.

Larger buildings and other miscellaneous infrastructure utilize a wider variety of foundation systems. The most common foundation types used for buildings in Norman Wells are steel pipe piles (23 per cent) and steel H-beam piles (13 per cent), timber sills (22 per cent), timber perimeter sills (12 per cent), and concrete strip footings (10 per cent). Special foundation systems such as ventilated gravel pads (Fig. 5c), thermosyphons, and steel pile sheeting are also used for large-scale infrastructure such as oil and water storage tanks and docks.

Performance history

In the past, the town of Norman Wells has experienced problems with roads, foundations, utilities, and embankments due to both natural and anthropogenic changes to permafrost. Dramatic examples of damage caused to early foundations by permafrost degradation have been amply illustrated in the literature (Hemstock, 1949; Pihlainen, 1951; Legget and Dickens, 1959; Johnston, 1981). Large buildings built after the Second World War and associated with the oil industry in Norman Wells were the first to show spectacular foundation problems (Fig. 6a). Over the years, construction methods and foundation systems have improved although problems related to permafrost degradation are still present and potentially will be enhanced as a result of climate warming.

Preliminary results indicate that a few existing structures are currently experiencing minor problems. Some of those problems concern light and linear infrastructure, such as a pipeline showing deformation in some locations due to freeze and thaw cycles (Fig. 6b), fences (Fig. 6c), and utilidor (gas/water distribution system and sewer collecting system). Buildings showing indications of deformation are those with a concrete floor standing on a gravel pad, such as garages or warehouses. These structures have generally been remediated and are being closely monitored. In Norman Wells, most buildings that have undergone extreme deformation, damaging the integrity of the structure, have been dismantled (Fig. 6a, d), notably many former Imperial Oil Ltd. installations. These earlier problems occurred mainly because of inappropriate foundation systems and ineffective drainage near the buildings. Currently, as most of the existing houses in Norman Wells stand on steel pipe piles, H-steel beam piles, or rail beam piles, all driven and anchored into bedrock,

Figure 6. a) Old warehouse affected by pile failure as shown by the arrow (courtesy of the National Research Council of Canada archives) (National Research Council, Division of Building Research no. BR9182 P-175); b) gravel berm over pipeline (indicated by the arrow) to remediate upward displacement of the pipe; c) light metal fence strongly affected by frost heaving, with vertical displacement up to about 1 m as indicated by arrrows; and d) timber posts of an abandoned building loosened by frost heaving and thaw settlement.

foundation problems associated with the ground thermal regime are not a concern. However, piles not anchored into bedrock (e.g. timber posts, Fig. 6d), shallow foundations not designed for a greater change in thermal stability of frozen soils, and structures standing on foundations that do not allow for differential ground movement are of potential concern.

Future work and discussion

The next phase of the pilot study will attempt to assess systematically the sensitivity of permafrost-affected infrastructure to current climate trends and to future climate change. The use of geothermal modelling to evaluate the response of currently disturbed and undisturbed ground, both with or without development, and to assess the associated impacts on infrastructure, will be critical to achieving this task. The combination of permafrost modelling and geotechnical evaluation will provide a methodological framework for assessing foundation performance and the potential for problematic ground conditions at the community level and will allow a first order estimate of the remedial costs involved. The project results will assist communities and authorities responsible for the design, construction, and maintenance of infrastructure (i.e. town public works departments) to develop adaptation plans incorporating climate change. This framework would provide the opportunity to expand research on infrastructure, permafrost, and climate-change scenarios to other northern communities and to determine thresholds at which the projected climate change impacts upon infrastructure would become significant. The community-level approach will contribute to a broader northern impact and adaptation priority-setting exercise and action plan.

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